IACHEC Thermal SNRs
Working Group Report
Thermal SNRs WG Current Membership

Andy Beardmore(Leicester), Sunil Chandra(CSRNWU), Konrad Dennerl(MPE), Jelle de Plaa(SRON), Gulab Dewangan(IUCAA), Adam Foster(SAO), Michael Freyberg(MPE), Terrance Gaetz(SAO), Brian Grefenstette(Caltech), Frank Haberl(MPE), Jelle Kaastra(SRON), Xi Long(SAO), Kristin Madsen(UMBC), Eric Miller(MIT), Paul Plucinsky(SAO), Andy Pollock(Sheffield), Manami Sasaki(Remeis Observatory & ECAP), Steve Sembay(Leicester), KP Singh(IISERM), Martin Stuhlinger(ESAC), Firoza Sutaria(TIFR), Hiroya Yamaguchi(ISAS)
**E0102: IACHEC Efforts**

- XMM RGS spectrum shows strong, well-separated lines of O, Ne, & Mg (Rasmussen et al. 2001)
- Model is used by Chandra and was used by Suzaku to verify contamination models and by Swift, ASTROSAT and NICER to search for contamination, gain and other purposes
- key data set for the Concordance paper (ACIS, pn, MOS, Suzaku, Swift)
- model available at “https://wikis.mit.edu/confluence/display/iachec/Thermal+SNR"

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**Chandra ACIS**

Red (0.3-0.5 keV), Green (0.5-0.75 keV)
Blue (0.75 – 7.0 keV)

**XMM RGS**

**Pollock (Sheffield)**

Red (0.3-0.5 keV), Green (0.5-0.75 keV)
Blue (0.75 – 7.0 keV)
Cas A: IACHEC Efforts

- Highest X-ray flux from a thermal SNR ($F_x=2.6\times10^{-9}$ ergs cm$^{-2}$ s$^{-1}$ [0.3-10.0 keV])
- Beardmore (Leicester) developed an IACHEC standard, empirical model, available at “https://wikis.mit.edu/confluence/display/iachec/Cas+A"
- Significant spectral variations with position due to different plasma conditions and bulk velocities
- CXC calibration team is starting to use Cas A in conjunction with the ACIS external calibration source for gain calibration
- Swift and ASTROSAT use Cas A for gain and CTI calibration

Chandra ACIS

Beardmore (Leicester)

XMM MOS1

O, Ne, Fe-L
Si continuum

6 arcmin
N132D

- Most X-ray luminous SNR in the Local Group
- Spectrum is more complicated than E0102, significant Fe-L and Fe-K emission and multiple (identified) temperature components (Behar et al. 2000, Suzuki et al. 2020)
- More spectral variation with position & slightly larger than E0102
- Routine calibration target for XMM and Chandra LP in 2019/2020

Chandra ACIS

Pollock (Sheffield)

XMM RGS Spectra of N132D and E0102

Red (0.3-0.75 keV), Green (0.8-1.1 keV), Blue (1.1 – 2.0 keV)
N132D: Model Development

- WG is developing two models currently, an empirical model (abs., nlapec, Gaussians) and a physical model (abs., vrnei or vapec, Gaussian)
- RGS data has driven the empirical model in the 0.3-1.5 keV range. Stuhlinger, Pollock & Guainazzi developed first version in 2012.
- Suzuki et al. 2020 published an analysis of the 1st and 2nd order RGS spectra, used in the physical model.
- Empirical model currently consists of:
  - two components for absorption (Galactic and LMC)
  - 120 Gaussians for the lines
  - three nlapec components for the continuum with:
    \( kT_1 = 0.18 \) keV
    \( kT_2 = 1.14 \) keV
    \( kT_3 = 5.48 \) keV
N132D: Model Development

- We must develop the model in different stages (energy ranges), given the sensitivities of the various instruments.
- Ideally we would go in order of flux, low energy range first, then the mid energy range next and finally the high energy range. But we jumped ahead to the high energy range.
- We should correct this and go in order of flux.

0.3-1.5 keV: RGS
1.5-4.5 keV: pn, MOS, ACIS, XRT, XIS
4.5-8.0 keV: NuSTAR, pn, MOS, ACIS, XIS

- Thermal SNRs WG has focussed recently on the high energy part of the spectrum taking advantage of the new information from NuSTAR (Grefenstette) and Suzaku (Miller), also Bamba et al. 2018.
- Results presented at this meeting will focus on the 4.5-8.0 keV range.
N132D General Fitting Instructions

- **fit in the 4.5 – 8.0 keV band** (the 8.0 keV is flexible, do what makes sense for your instrument)
- **use unbinned spectra** for fitting or use Kaastra's optimal binning method using the ftool optimal binning (using 'ftgrouppha' with 'bintype=opt')
- **use an explicit background model** for your instrument, do not subtract background
- vary what parameters make sense for your background model, hopefully this is just a normalization
- **use the C statistic** as the fit statistic to determine the best fit
- use the Pearson chi square or chi square with the weighting by the model for test statistic
- report the C statistic, Pearson chi square and DOF for the fits
- run the goodness command in xspec with the default settings of "sim" and "fit" to evaluate the goodness of the fit.
Physical Model Fitting Instructions

- **allow the global norm** to vary \((n132d:1)\)
- Freeze the normalization of the high kT vrnei component (currently 4.77464 keV) and do NOT allow it to vary \((n132d:189)\)
- set the neutral Fe K line normalization to 0 and freeze it \((n132d:192)\)
- report C statistic, Pearson chi square, and DOF
- report the best fit value of the global normalization with 1 sigma uncertainty (this is the only free parameter in the source model)
- report the flux in the 4.5–8.0 keV band with 1 sigma uncertainty

Model is called “n132d_afoster_suzuki_vrnei_20210420.mdl” and is available on the IACHEC wiki page:
https://wikis.mit.edu/confluence/display/iachec/Current+N132D+model

Only one free parameter in the source model, a global normalization. For this exercise, we are assuming a spectral shape, evaluating if that shape fits the data well. If yes, then we will compare the fitted values of the normalization and flux.
Empirical Model Fitting Instructions

- freeze the normalization of the neutral Fe line to 0.0
- allow the Global Norm to vary (source:1)
- freeze the normalization of the high kT component and do NOT allow it to vary (source:419)
- allow the normalization of the Fe XXV He-alpha f line (source:390) to vary, the normalizations of the Fe XXV He-alpha f and i lines are linked to the normalization of the Fe XXV He-alpha r line. So, only one normalization in the Fe XVII He-alpha triplet is allowed to vary.
- allow the normalization of the Fe XXVI Ly-alpha line (source:399) to vary
- there should be only three free parameters in the source model, source1, source:390, and source:399
- report C statistic, Pearson chi square, and DOF
- report the result of the goodness command
- report the best fitted values with 1 sigma uncertainties (delta C statistic of 1.0) for the Global Norm, normalization of the Fe XXV He-alpha r line, and the normalization of the Fe XXVI Ly-alpha line
- report the flux in the 4.5-8.0 keV band with 1 sigma uncertainty

Only three free parameters in the source model, all are normalizations.

Model is called “N132D_E0310_v2.13_20210421.mdl” and is available on the IACHEC wiki page:
https://wikis.mit.edu/confluence/display/iachec/Current+N132D+model
### The Spectral Fitters

*Those who did the work:*

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Developer</th>
</tr>
</thead>
<tbody>
<tr>
<td>NuSTAR</td>
<td>Brian Grefenstette (Caltech)</td>
</tr>
<tr>
<td>Suzaku XIS</td>
<td>Eric Miller (MIT)</td>
</tr>
<tr>
<td>XMM pn &amp; MOS</td>
<td>Adam Foster (SAO)</td>
</tr>
<tr>
<td>Models</td>
<td>Adam Foster (SAO)</td>
</tr>
<tr>
<td>XMM-RGS</td>
<td>Martin Stuhlinger (ESAC)</td>
</tr>
<tr>
<td>Chandra ACIS</td>
<td>Paul Plucinsky (SAO)</td>
</tr>
<tr>
<td>Swift XRT</td>
<td>Andrew Beardmore (Leicester)</td>
</tr>
</tbody>
</table>
Development of Physical Model and Fits to the pn and MOS Data

Adam Foster presents this
ACIS: 2006 data fit 4.5-8.0 keV with the physical model. Only the global norm & detector norm are allowed to vary.

Global Norm = 1.19
CStat = 1617
DOF = 1432
PChi = 1.02
Goodness = 65.0%

N132D: ACIS 2006 data (5532,7259,7266), afost 20210420 XMM model, CStat=1617
DOF=1432, PChi=1.02, Gl Norm=1.19, freeze high kT norm

1.36 keV
4.77 keV
Suzaku XIS0: 4.5-8.0 keV with the physical model. Only the global norm & detector norm are allowed to vary.

Global Norm = 1.14
CStat = 522
DOF = 481
PChi = 1.03
Goodness = 84.0%
Physical model, un-binned

NuSTAR: 4.5-8.0 keV
FPMA & FPMB physical model. Only the global norm & detector norm are allowed to vary.

Global Norm = 1.04, 1.15
CStat = 179
DOF = 169
PChi = 1.09
Goodness = 76.0%

Grefenstette (Caltech)
Physical model, un-binned

NuSTAR : 4.5-8.0 keV
FPMA & FPMB physical model.
Only the global norm & detector norm are allowed to vary.

Global Norm = 1.04, 1.15
CStat = 179
DOF = 169
PChi = 1.09
Goodness = 76.0%

Grefenstette (Caltech)

Counts sec^{-1} keV^{-1}

Energy (keV)

Total
Suzuki
cold vrnei
1.36 keV vrnei
4.8 keV vrnei

Paul Plucinsky
Swift XRT: 4.5-8.0 keV physical model. Only the global norm & detector norm are allowed to vary.

Global Norm= 1.03
CStat=576
DOF=548
PChi=0.89
Goodness= 3.0%
ACIS: 2006 data fit 0.35–10.0 keV with the physical model. Only the global norm & detector norm are allowed to vary.

Global Norm = 1.37
CStat = 179
DOF = 169
PChi = 3.37
Goodness = 100%

N132D: ACIS 2006 data (5532.7259,7266), afoster 20210420 XMM model, CStat=13432 fit 0.35–10.0 keV, DOF=3970, PChi=3.37, Gl Norm=1.37, Bkg Norm=0.83, vnei frozen
Stuhlinger (ESAC)

N132D

Foster model:
(5.5 keV component frozen)

No fit:
Red.Chi: 54 (337104/6187)

Fit norm:
p135: 4.31616E-02+/−4.97e-05
Red.Chi: 49 (300487/6187)

Fit constant:
p1: 1.155+/−001
Red.Chi: 49 (300253/6187)
## Physical Model Fit Results

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Gl. Norm</th>
<th>Flux [4.5-8.0 keV] (erg cm(^{-2}) s(^{-1}))</th>
<th>CStat</th>
<th>DOF</th>
<th>PChi</th>
<th>Goodness</th>
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<tbody>
<tr>
<td>initial</td>
<td>1.00</td>
<td>0.94_E-12</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>ACIS</td>
<td>1.19+/−0.03</td>
<td>1.13+/−0.03 E-12</td>
<td>1617</td>
<td>1432</td>
<td>1.02</td>
<td>69%</td>
</tr>
<tr>
<td>Suzaku XIS0</td>
<td>1.14+/−0.02</td>
<td>1.07+/−0.02 E-12</td>
<td>522</td>
<td>481</td>
<td>1.03</td>
<td>84%</td>
</tr>
<tr>
<td>NuSTAR FPMA</td>
<td>1.04+/−0.05</td>
<td>0.99+/−0.03 E-12</td>
<td>179</td>
<td>169</td>
<td>1.09</td>
<td>76%</td>
</tr>
<tr>
<td>NuSTAR FPMB</td>
<td>1.15+/−0.06</td>
<td>1.07+/−0.05 E-12</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>pn</td>
<td>1.00+/−0.01</td>
<td>0.96+/−0.01 E-12</td>
<td>13122</td>
<td>11882</td>
<td>1.02</td>
<td>96%</td>
</tr>
<tr>
<td>MOS1</td>
<td>1.04+/−0.01</td>
<td>1.00+/−0.01 E-12</td>
<td>21288</td>
<td>26561</td>
<td>0.98</td>
<td>27%</td>
</tr>
<tr>
<td>MOS2</td>
<td>0.97+/−0.01</td>
<td>0.93+/−0.01 E-12</td>
<td>21681</td>
<td>26561</td>
<td>0.99</td>
<td>30%</td>
</tr>
<tr>
<td>Swift</td>
<td>1.03+/−0.09</td>
<td>0.93+/−0.09 E-12</td>
<td>576</td>
<td>548</td>
<td>0.89</td>
<td>3%</td>
</tr>
</tbody>
</table>
Physical Model Flux Results

N132D: physical model flux [4.5–8.0 keV], 17 May 2021
ACIS: 2006 data fit 4.5–8.0 keV with the empirical model. Global norm, Fe XXV He-α norm and Fe XXVI Ly-α norm are allowed to vary.

Global Norm = 0.97
CStat = 1621
DOF = 1424
PChi = 1.04
Goodness = 80.0%

N132D: ACIS 2006 data (5532,7259,7266), N132D_E0310_v2.13_20210421, CStat=1621
fit only 4.5–8.0 keV, DOF=1424, PChi=1.04, Gl Norm=0.97, freeze high kT norm.
Suzaku XIS0: 4.5-8.0 keV with the empirical model. Global norm, Fe XXV He-α norm and Fe XXVI Ly-α norm & detector norm are allowed to vary.

Global Norm = 0.83
CStat = 544
DOF = 478
PChi = 1.07
Goodness = 96.0%

Paul Plucinsky
Empirical Model (v2.13), un-binned

NuSTAR: 4.5-8.0 keV
FPMA&B empirical model.
Global norm, Fe XXV He-α norm and Fe XXVI Ly-α norm & detector norm are allowed to vary.
Global Norm = 0.79, 0.87
CStat = 183
DOF = 168
PChi = 1.10
Goodness = 87.0%

Grefenstette (Caltech)
Empirical Model (v2.13), un-binned

NuSTAR : 4.5-8.0 keV
FPMA&B empirical model.
Global norm, Fe XXV He-α norm and Fe XXVI Ly-α norm & detector norm are allowed to vary.
Global Norm= 0.79, 0.87
CStat=183
DOF=168
PChi=1.10
Goodness= 87.0%
Swift XRT: 4.5-8.0 keV empirical model.
Global norm Fe XXV He-α norm, Fe XXVI Ly-α norm & detector norm are allowed to vary.

Global Norm = 0.78
CStat = 574
DOF = 546
PChi = 0.89
Goodness = 3.0%
ACIS: 2006 data fit 0.35-10.0 keV with the empirical model. Global norm & detector bkg norm are allowed to vary. All other parameters frozen.

Global Norm= 1.04
CStat=7944 DOF=3970 PChi=1.93
Stuhlinger (ESAC)

N132D

RGS based model:

V2.13 continuum fixed
132 lines

Fit:
Red.Chi: 6 (38400/6187)

Available as:
N132D_E0310_v2.14
### Empirical Model Fit Results

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Gl. Norm</th>
<th>Flux [4.5-8.0 keV] (erg cm(^{-2}) s(^{-1}))</th>
<th>Fe XXV He-(\alpha) f (photons cm(^{-2}) s(^{-1}))</th>
<th>Fe XXVI Ly-(\alpha) (photons cm(^{-2}) s(^{-1}))</th>
<th>CStat</th>
<th>DOF</th>
<th>PChi</th>
<th>Goodness</th>
</tr>
</thead>
<tbody>
<tr>
<td>initial</td>
<td>1.00</td>
<td>1.24_E-12</td>
<td>3.0E-06</td>
<td>2.2E-07</td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>ACIS</td>
<td>0.97+/-0.02</td>
<td>1.09+/-0.03 E-12</td>
<td>3.7+/-.3 E-06</td>
<td>8.8+/-?? E-07</td>
<td>1621</td>
<td>1424</td>
<td>1.04</td>
<td>80%</td>
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<tr>
<td>Suzaku XIS0</td>
<td>0.83+/-0.01</td>
<td>1.07+/-0.01 E-12</td>
<td>3.9+/-.2 E-06</td>
<td>13.0+/-.6 E-07</td>
<td>544</td>
<td>478</td>
<td>1.07</td>
<td>96%</td>
</tr>
<tr>
<td>NuSTAR FPMA</td>
<td>0.79+/-0.05</td>
<td>0.99+/-0.02 E-12</td>
<td>3.6+/-.5 E-06</td>
<td>2.0+/-?? E-10</td>
<td>183</td>
<td>168</td>
<td>1.10</td>
<td>87%</td>
</tr>
<tr>
<td>NuSTAR FPMB</td>
<td>0.87+/-0.04</td>
<td>1.09+/-0.03 E-12</td>
<td>same</td>
<td>same</td>
<td>*</td>
<td>*</td>
<td>*</td>
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</tr>
<tr>
<td>pn</td>
<td>0.75+/-0.01</td>
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<td>3.6+/-.1 E-06</td>
<td>1.8+/-0.2 E-7</td>
<td>13181</td>
<td>11880</td>
<td>1.04</td>
<td>100%</td>
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<tr>
<td>MOS1</td>
<td>0.77+/-0.01</td>
<td>0.99+/-0.01 E-12</td>
<td>3.9+/-.1 E-06</td>
<td>1.5+/-0.4 E-7</td>
<td>21303</td>
<td>26559</td>
<td>1.00</td>
<td>51%</td>
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<tr>
<td>MOS2</td>
<td>0.71+/-0.01</td>
<td>0.92+/-0.01 E-12</td>
<td>3.9+/-.1 E-06</td>
<td>2.3+/-0.4 E-7</td>
<td>21724</td>
<td>26559</td>
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<td>Swift</td>
<td>0.78+/-0.07</td>
<td>1.15+/-0.12 E-12</td>
<td>2.3+/-1.4 E-06</td>
<td>??</td>
<td>574</td>
<td>546</td>
<td>0.89</td>
<td>3%</td>
</tr>
</tbody>
</table>
Empirical Model Flux Results

N132D: empirical model flux [4.5–8.0 keV], 17 May 2021
Conclusions

• physical model and empirical model have similar parameters for the continuum and similar strengths of Fe XXV He-α triplet, hopefully this means that the empirical model has some basis in reality
• physical model and empirical model fit equally well in the 4.5-8.0 keV band IF the global normalization is allowed to vary
• the overall shape of the spectrum is similar amongst the various instruments in this bandpass
• there are significant flux differences in this band with ACIS having the highest flux and MOS2 having the lowest flux
Future Work

• go back to the original order of model development, low energy part first, middle energy next, high energy last
• want to preserve what we have done for the high energy part of the spectrum
• finalize the low energy part of the model, based on analysis of the RGS
• schedule: finish low energy part this summer and have candidate model for middle range BEFORE the IACHEC meeting in the Fall
• finalize the middle range model at the Fall meeting
Data selected to ensure similar modes, filters and that the remnant is on the chip.

### Detector background:
- Fit model from 4.5 to 12.0 keV. Detector BG model is loaded, but with overall norm free for each detector. Fit to get background norm, then freeze.

### N132D fit
- Reset range to 4.5-8keV, Freeze all model components except those listed.
Suzuki model: 3x ionizing plasmas
- Same timescale ($\tau=9.8\times10^{10}\text{cm}^{-3}\text{s}^{-1}$)
- Same elemental abundances
- Different $kT$

These components do not describe high $kT$. From Bamba+ (2018)
There is a $\sim5.7\text{keV}$ component too and evidence for a neutral Fe line.

Added one extra vrnei component for high $kT$ plasma. Set to $4.8\text{keV}$ based on fits to this data.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_H$</td>
<td>$(10^{20} \text{ cm}^{-2})$</td>
</tr>
<tr>
<td>$kT_{\text{e,low}}$</td>
<td>(keV)</td>
</tr>
<tr>
<td>$VEM_{\text{low}}$</td>
<td>$(10^6 \text{ cm}^{-3})$</td>
</tr>
<tr>
<td>$\sigma_{\text{low}}$</td>
<td>(km s$^{-1}$)</td>
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<tr>
<td>$v_{\text{low}}$</td>
<td>(km s$^{-1}$)</td>
</tr>
<tr>
<td>$kT_{\text{e,med}}$</td>
<td>(keV)</td>
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<tr>
<td>$VEM_{\text{med}}$</td>
<td>$(10^6 \text{ cm}^{-3})$</td>
</tr>
<tr>
<td>$\sigma_{\text{med}}$</td>
<td>(km s$^{-1}$)</td>
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<tr>
<td>$v_{\text{med}}$</td>
<td>(km s$^{-1}$)</td>
</tr>
<tr>
<td>$kT_{\text{e,high}}$</td>
<td>(keV)</td>
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<tr>
<td>$VEM_{\text{high}}$</td>
<td>$(10^6 \text{ cm}^{-3})$</td>
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<tr>
<td>$\sigma_{\text{high}}$</td>
<td>(km s$^{-1}$)</td>
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<tr>
<td>$v_{\text{high}}$</td>
<td>(km s$^{-1}$)</td>
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<tr>
<td>$n_{\text{e}}$</td>
<td>$(10^{10} \text{ cm}^{-3})$</td>
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<tr>
<td>C-statistics/dof</td>
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</table>
Physical model with Components shown

1.36 keV

4.8 keV
## Parameters

### Physical Model

<table>
<thead>
<tr>
<th>Instrument</th>
<th>GI Norm</th>
<th>Flux</th>
<th>Cstat</th>
<th>DOF</th>
<th>Pchi</th>
<th>Goodness</th>
</tr>
</thead>
<tbody>
<tr>
<td>PN</td>
<td>1.001+/-0.006</td>
<td>9.58 +/-0.06</td>
<td>13122</td>
<td>11882</td>
<td>12160</td>
<td>96.00%</td>
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<tr>
<td>MOS1</td>
<td>1.039+/-0.009</td>
<td>9.95 +/-0.09</td>
<td>21288</td>
<td>26561</td>
<td>26201</td>
<td>27.00%</td>
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<tr>
<td>MOS2</td>
<td>0.966 +/ -0.009</td>
<td>9.25+/-0.09</td>
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<td>26352</td>
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<tr>
<td>ALL</td>
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<td>9.58 +/-0.04</td>
<td>56118</td>
<td>65006</td>
<td>64762</td>
<td>27.00%</td>
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</table>

### Empirical Model

<table>
<thead>
<tr>
<th>Instrument</th>
<th>GI Norm</th>
<th>Flux</th>
<th>Fe XXV He-a (E-6)</th>
<th>Fe XXVI Lya (E-6)</th>
<th>Cstat</th>
<th>DOF</th>
<th>Pchi</th>
<th>Goodness</th>
</tr>
</thead>
<tbody>
<tr>
<td>PN</td>
<td>0.749+/-0.005</td>
<td>9.52+/-0.06</td>
<td>3.55+/-0.07</td>
<td>1.80+/-0.21</td>
<td>13181</td>
<td>11880</td>
<td>12336</td>
<td>100.00%</td>
</tr>
<tr>
<td>MOS1</td>
<td>0.767+/-0.008</td>
<td>9.87+/-0.10</td>
<td>3.86+/-0.14</td>
<td>1.46+/-0.38</td>
<td>21303</td>
<td>26559</td>
<td>26513</td>
<td>51.00%</td>
</tr>
<tr>
<td>MOS2</td>
<td>0.711+/-0.007</td>
<td>9.22+/-0.09</td>
<td>3.89+/-0.14</td>
<td>2.26+/-0.39</td>
<td>21724</td>
<td>26559</td>
<td>26588</td>
<td>49.00%</td>
</tr>
<tr>
<td>ALL</td>
<td>0.743+/-0.004</td>
<td>9.51+/-0.04</td>
<td>3.68+/-0.06</td>
<td>1.83+/-0.17</td>
<td>56242</td>
<td>65004</td>
<td>65486</td>
<td>82.00%</td>
</tr>
</tbody>
</table>